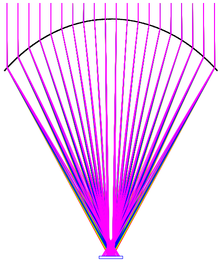
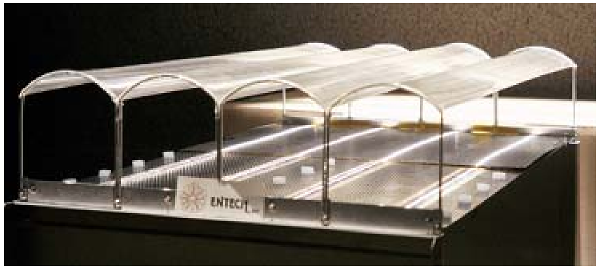


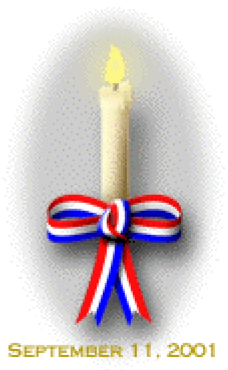


Acknowledgment: This Work Has Been Supported by Several NASA Programs

Stretched Lens Array (SLA) and Its Application to Space Solar Power (SSP)

Presented at the Space Solar Power Concept & Technology Maturation (SCTM) Program Technical Interchange Meeting (TIM)

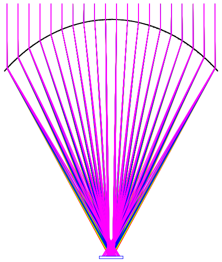
Ohio Aerospace Institute
September 10-12, 2002



M.J. O'Neill
ENTECH, Inc.
1077 Chisolm Trail
Keller, TX 76248 USA
Tel: 817-379-0100 Fax: 817-379-0300
E-Mail: mjoneill@entechsolar.com
Web Site: www.entechsolar.com

U.S. Patents 4,069,812, 4,711,972, 6,031,179, and 6,075,200.

ENTECH, INC.



SLA Development Team

- **Industry**
  - ENTECH: Lens and Photovoltaic (PV) Receiver Design & Fabrication
  - ABLE Engineering: Panel Design & Array Integration
  - 3M: Space-Qualified DC 93-500 Silicone Lensfilm Mass-Production
  - Rockwell Scientific/ZC&R Coatings: UV-Rejection and AO Protection Coating for Silicone Lensfilm
  - Spectrolab: High-Efficiency Triple-Junction Solar Cells
  - EMCORE: High-Efficiency Triple-Junction Solar Cells
  - JX Crystals: High-Efficiency Triple-Junction Solar Cells
  - Space Systems Loral: Commercial Space Mission Needs
- **NASA**
  - NASA MSFC: Space Durability Testing of Lens and NASA Mission Needs
  - NASA GRC: PV Receiver Design & Cell and Panel Performance Testing
  - NASA LaRC: Stretched Lens Membrane Structural Analysis & Testing
- **DOD**
  - AFRL: Military Space Mission Needs
- **Academia**
  - Auburn Space Power Institute: Micrometeoroid Tests at High Voltage

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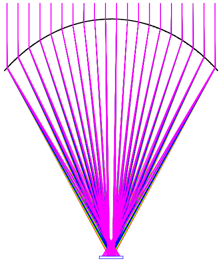
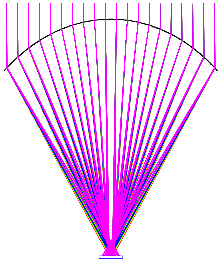
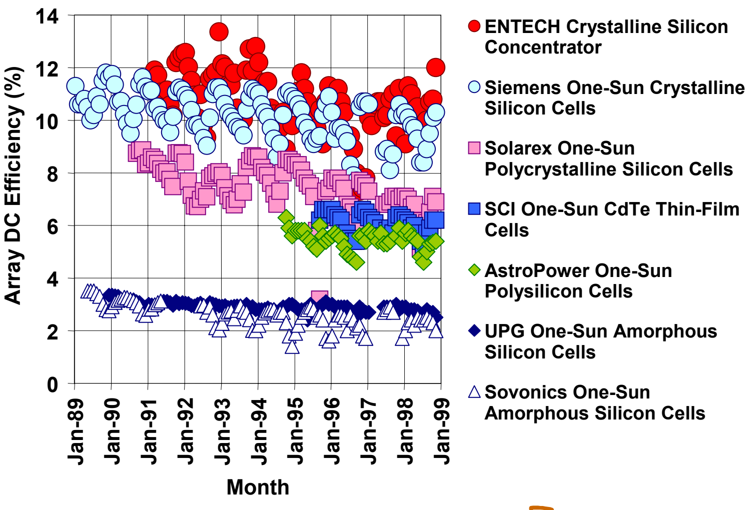


Background



Heritage: 20-Sun Silicon-Cell-Based Terrestrial Concentrators

- Large-Area (3 m^2) Module Uses 84-cm-Wide Acrylic Lens Focusing Onto 4-cm-Wide Silicon Cells (Modified One-Sun) Mounted to Extruded Aluminum Heat Sink
- Same Module Used in 2-Module *SunLine®* Array or 72-Module *SolarRow®* Array
- SolarRow Array at PVUSA-Davis Out-Performed Competing Technologies for Many Years – See Graph at Right



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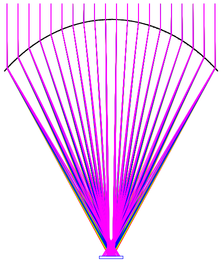
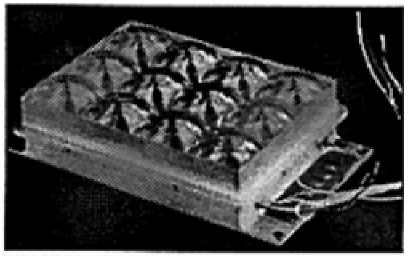
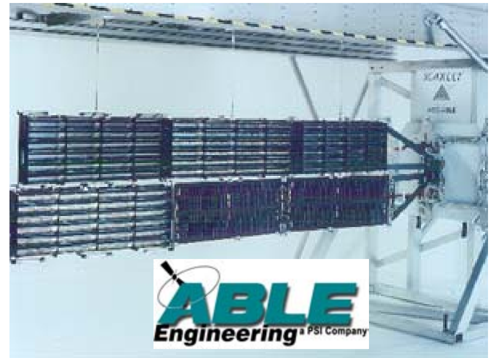


Heritage: Space Fresnel Lens Multi-Junction-Cell Photovoltaic Concentrators

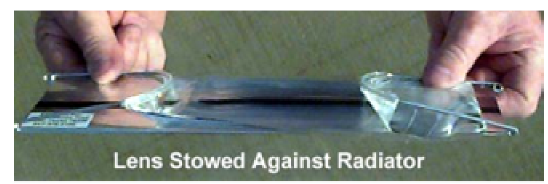


Mini-Dome Lenses on PASP+ in 1994

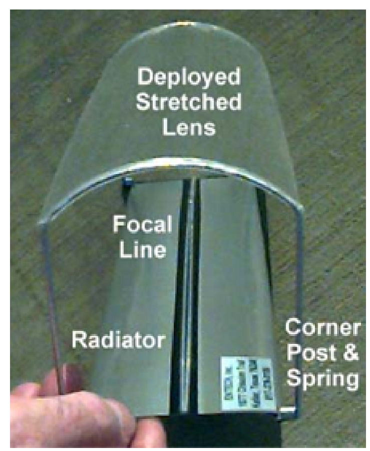


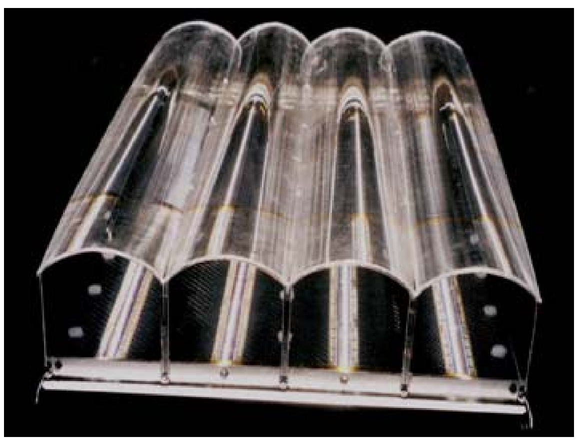
SCARLET 1 Lenses on COMET/METEOR in 1995

SCARLET 2 Lenses on Deep Space 1 in 1998



Stretched Lens in 1998





Stretched Lenses and Photovoltaic Receivers in 2000: 27% Net Module Efficiency

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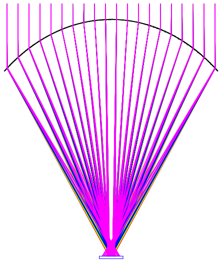
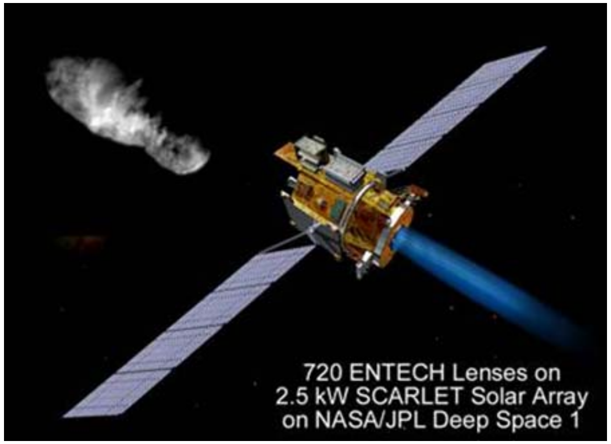
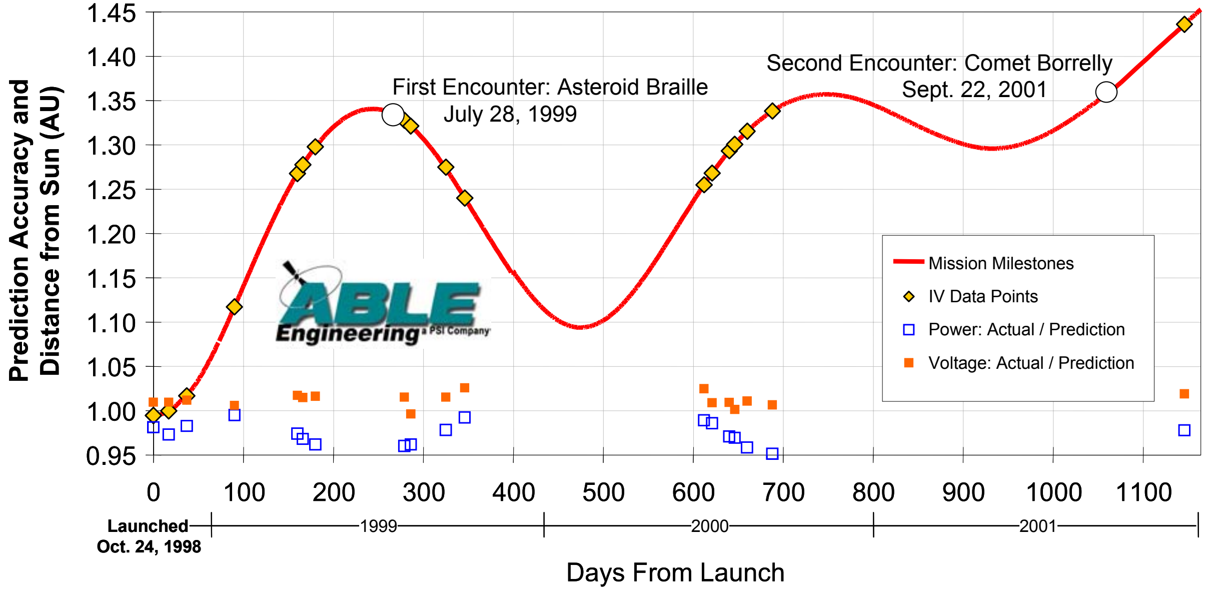


Heritage: Multi-Junction-Cell Based Concentrators for Space Power





- The SCARLET Concentrator Array on Deep Space 1 Was the First Flight of Triple-Junction Cells as the Primary Power for a Spacecraft
- The SCARLET Array Performed Flawlessly in Powering Both the Spacecraft and the Ion Engine for More than 3 Years, to Successful Rendezvous with Both the Asteroid, Braille, and the Comet, Borrelly
- Measured Power Still Matched Predictions Within ± 2% at Mission's End in December 2001

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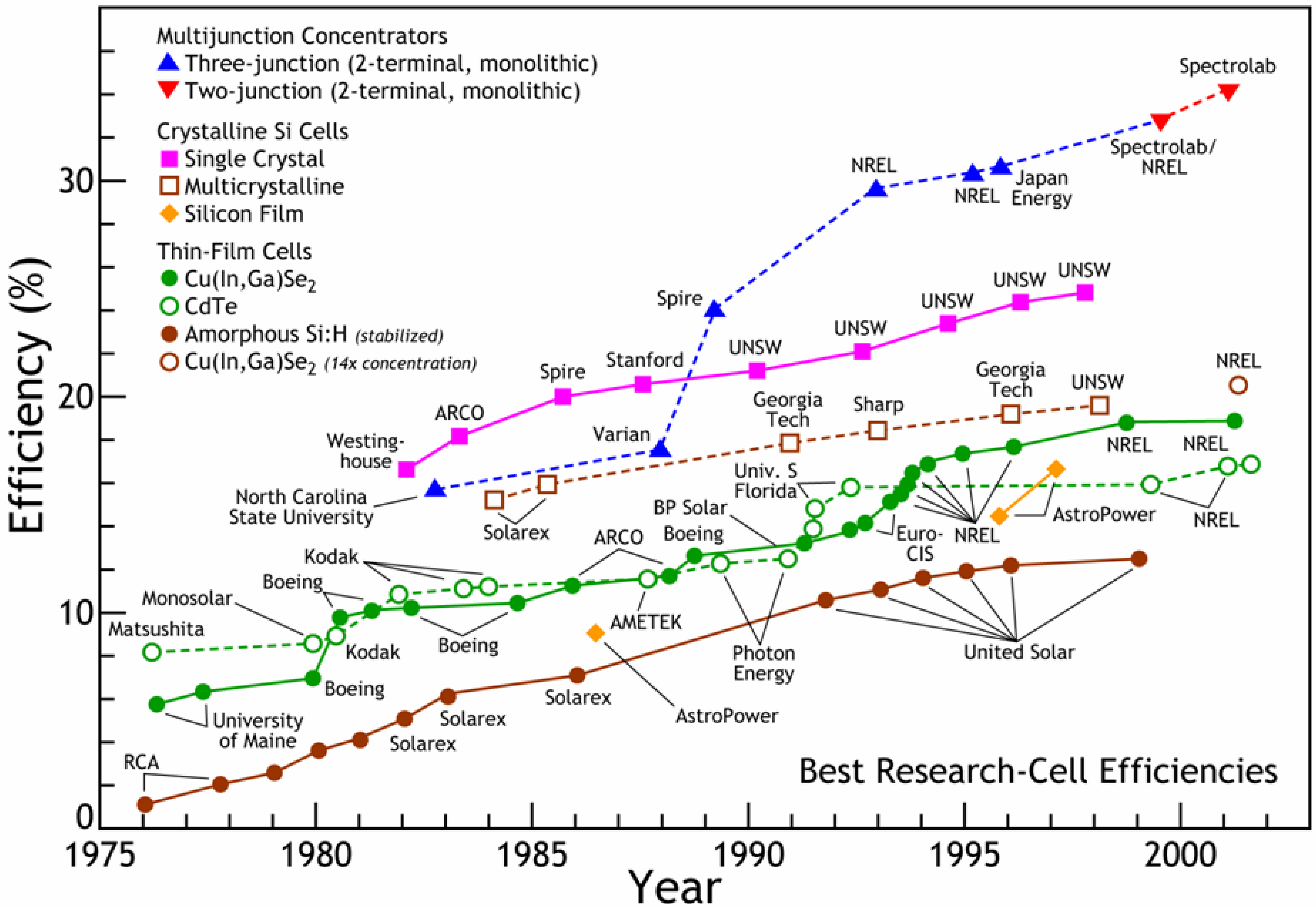
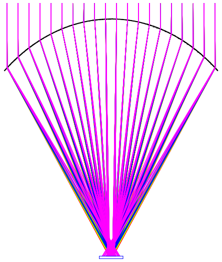
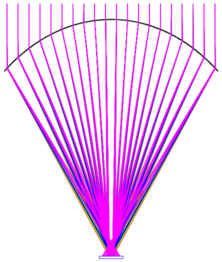
Terrestrial Cell Efficiencies Over Time – from DOE's Strategic Program Review March 2002



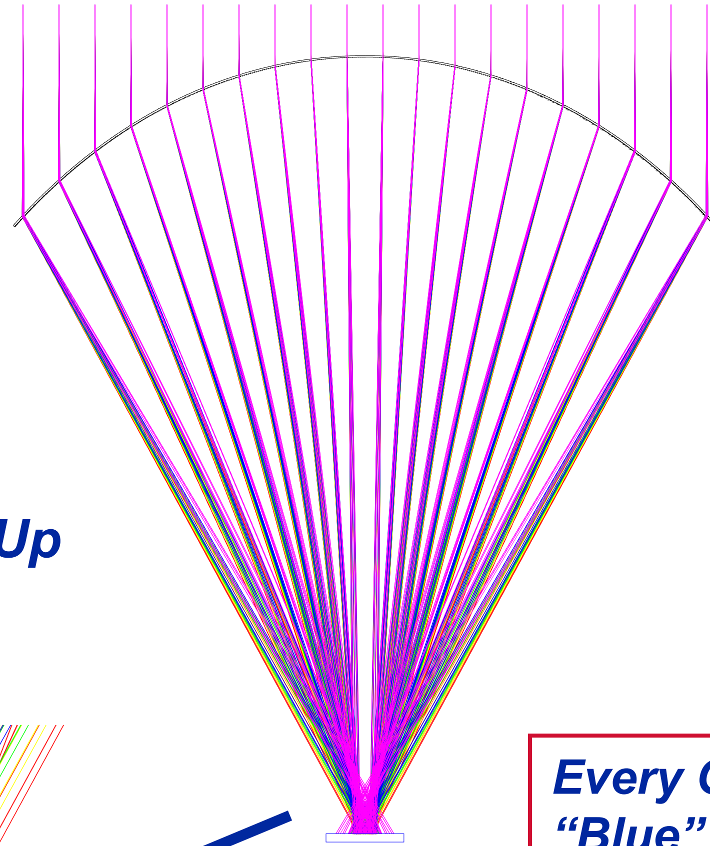


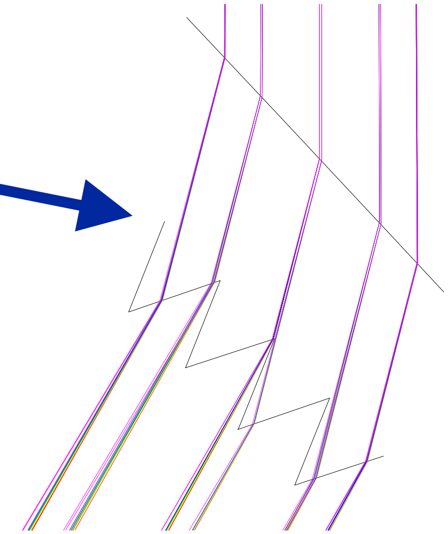
Optics



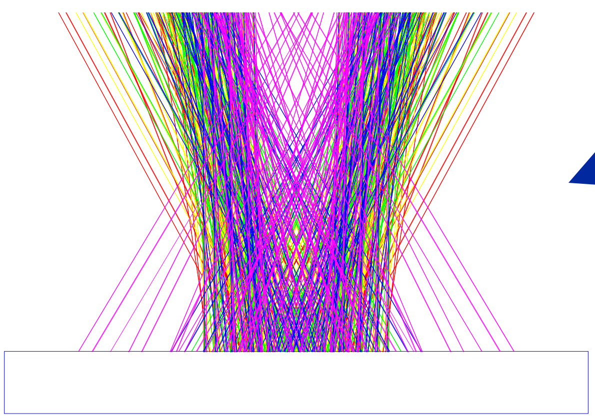
Ray Trace for Color-Mixing Fresnel Lens

U.S. Patents
4,069,812
6,031,179
6,075,200





Lens Close-Up



Receiver Close-Up

Every Other Prism Overlaps the "Blue" in Its Image with the "Red" in the Neighboring Prism's Image

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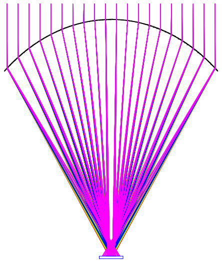
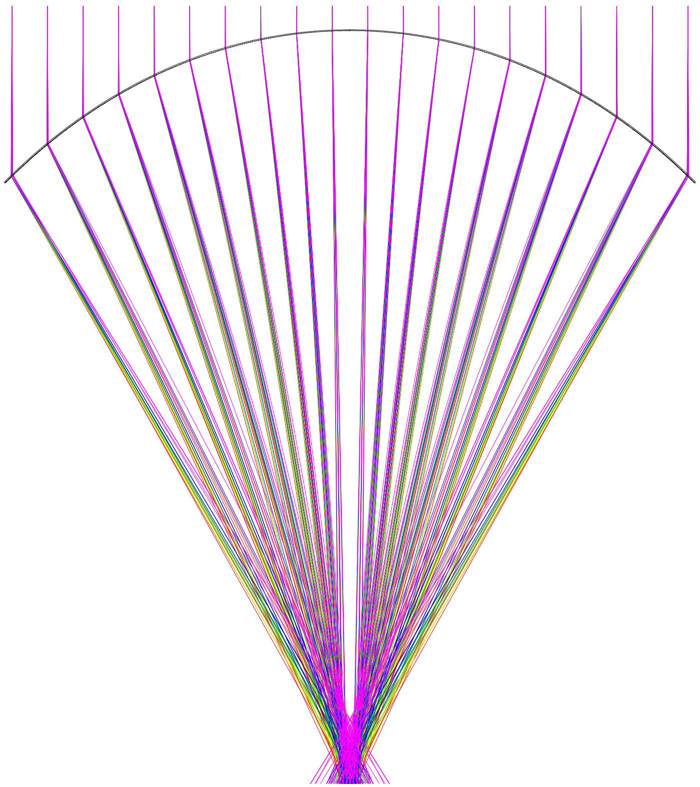
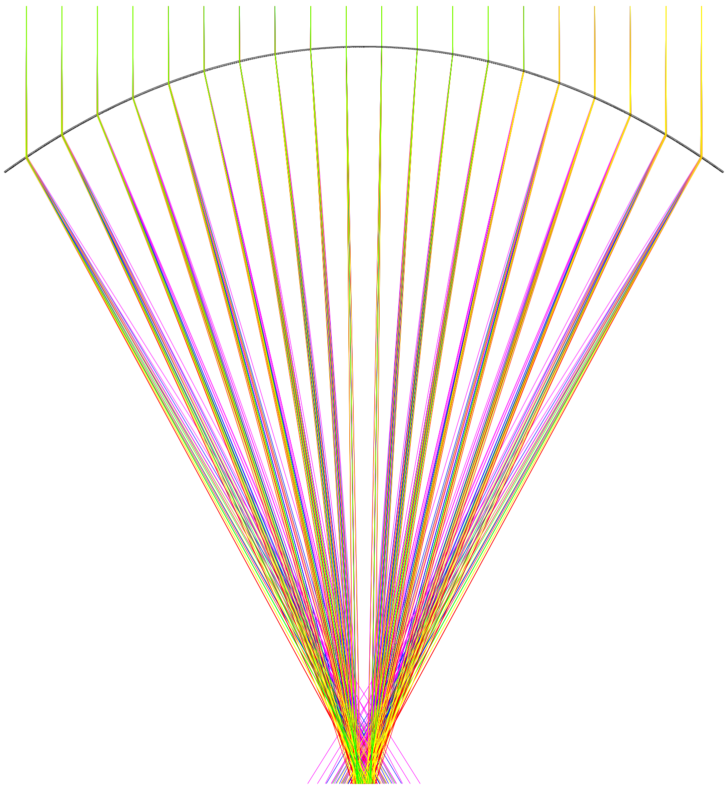


Color-Mixing Lens Shape Error Tolerance

Undistorted Lens



Distorted Lens: Flattened and Sagged with 10° Edge Slope Errors



Conclusion: Even Huge Shape Errors Have Only Small Effects on Optical Performance

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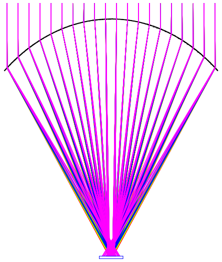

New Ultra-Thin Lensfilm Material

- 3M Successfully Completed a Trial Run (20 sq.m.) of Ultra-Thin DC93-500 Lensfilm
  - 100 Micron Tall Prisms
  - 90 Micron Base Thickness
  - 140 Micron Mass-Equivalent Thickness Since Triangular Prisms Fill Half of 100 Microns
- ENTECH Tested the Lenfilm for Optical Performance Using an NREL-Furnished Single-Junction GaInP Reference Concentrator Cell, as Shown in Photo
  - 91-93% Net Optical Efficiency
  - Same as for Previous Thicker Lensfilm (100 Micron Tall Prisms on 180 Micron Base)
- New Lensfilm Mass Is 40% Lower than Previous Lensfilm Mass

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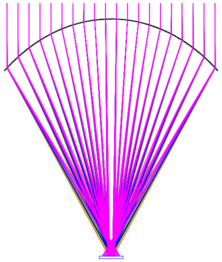
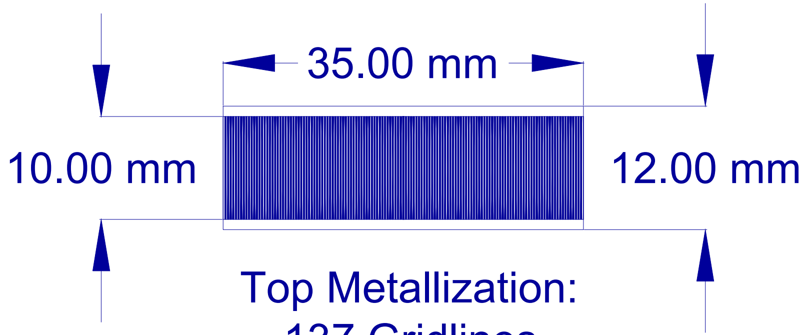
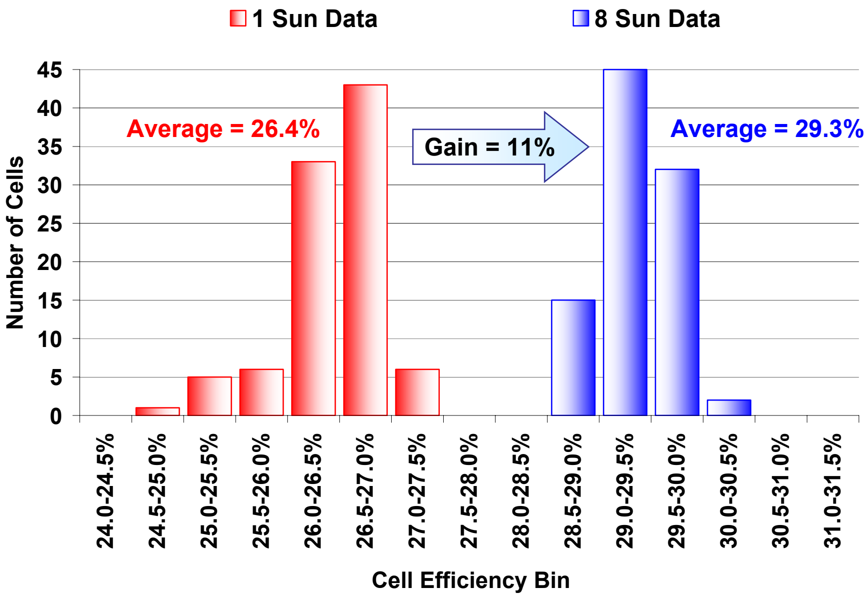


Cells

Latest Triple-Junction Space Solar Cell for the Stretched Lens Array (SLA)

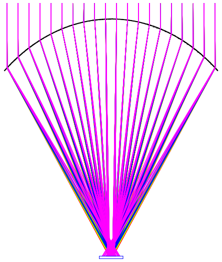


Top Metallization:
137 Gridlines
on 254 Micron
Centers Between
Dual Busbars

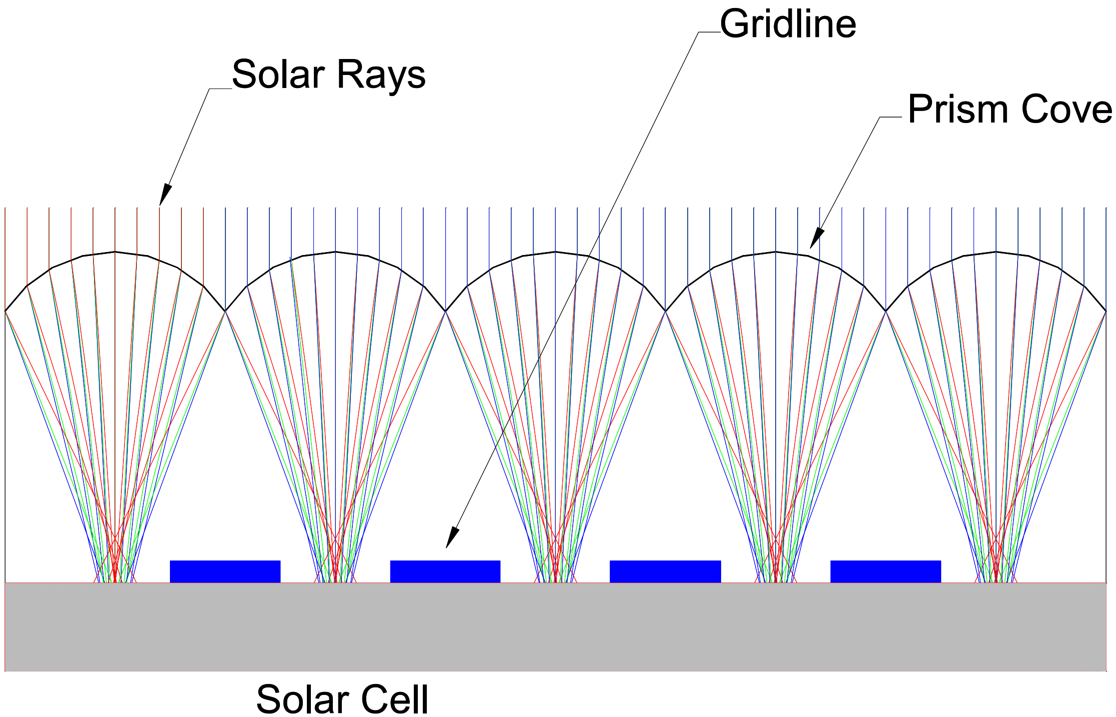


GaInP/GaAs/Ge Triple-Junction Cell Is Compatible with Silicone Prism Cover or Conventional Microsheet Cover Glass

Bare Cell Efficiency Distribution at 1 Sun and 8 Suns (AM0)



Solar Cell Prism Cover



Cross-Sectional Blowup of Silicone Prism Cover Used with GaInP/GaAs/Ge Multijunction Solar Cell

Prism Cover Eliminates Grid Shadow Loss

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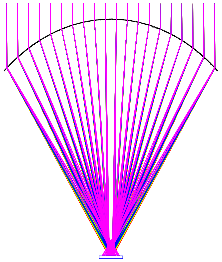
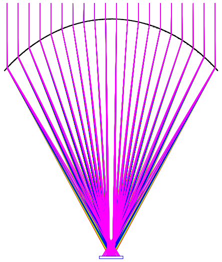
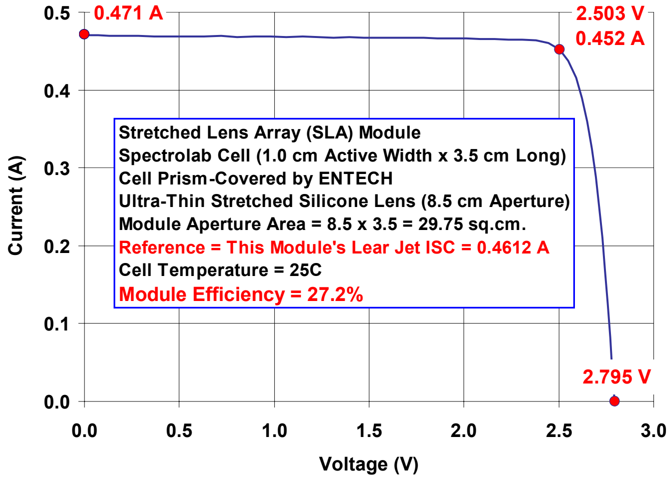


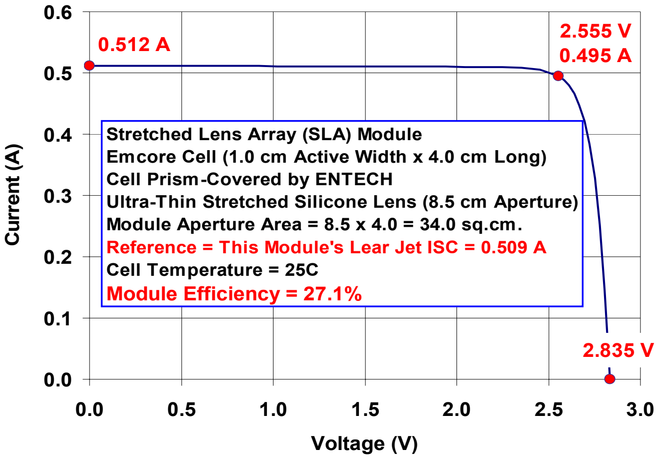
Lens/Cell Modules



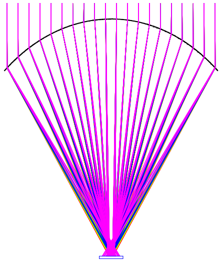
27% Net Lens/Cell Module Efficiency (AM0)

- NASA Glenn Recently Flew Lens/Cell Modules (Photo) on the Lear Jet to Measure AM0 Short-Circuit Currents
- NASA Glenn Used Lear Results to Set Lamps and Calibrate Full IV Curves in LAPSS Tests
- Modules with Prism-Covered Cells from Both Emcore and Spectrolab Exceeded 27% Net Efficiency at 25C, AM0





ENTECH, INC.



Full Array

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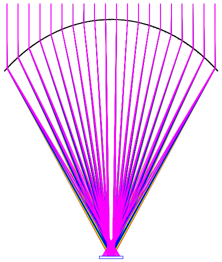
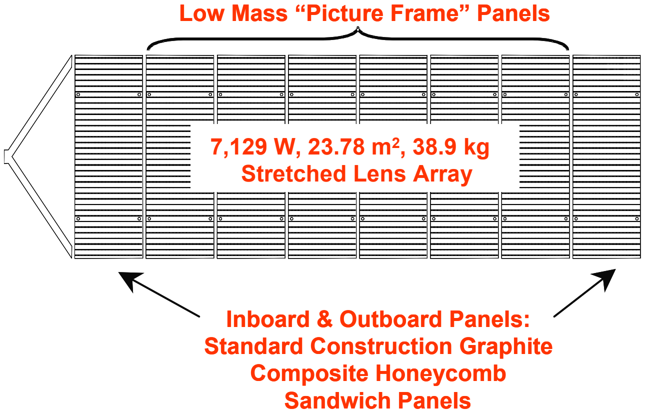
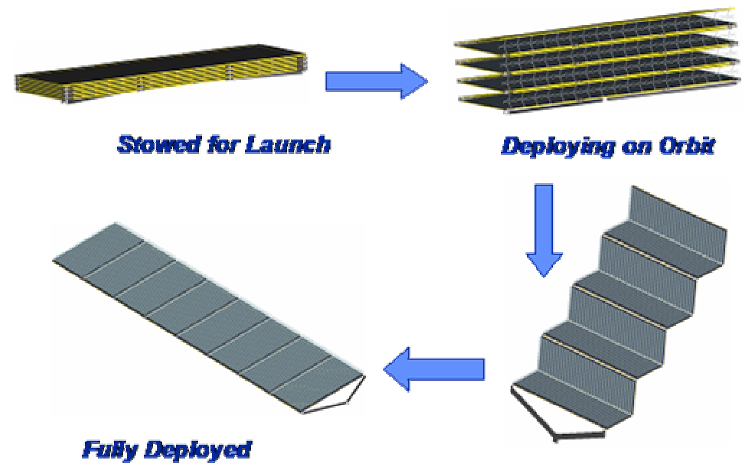


7 kW SLA Wing Attributes





Feature	Value or Characteristic
Point Design Basis	7,129 Watts (BOL)
SLA Implementation	Pop-up lenses
Base Platform Design Maturity	Most components flight proven on DS1
Specific Power	183 W/kg
Stowed Volume	0.11 m^3/kW
Stowed Stiffness	40 Hz
Deployed Stiffness	0.1 Hz
Stowed Power	Easily implemented on outer panel
Ease of Adding Planar Panel	Easily implemented on outer panel
Flatness & Warping	Well understood flat stable platform
Deployment Testing	Can use existing off-loaders
Power Testing	Pop-up lenses allow each panel to be tested as a complete assembly before wing integration
Commercial Appeal	Easier to integrate on commercial spacecraft. Readily accepted configuration.
Self Shadowing	No self shadowing

Current Technology SLA Wing-Level Beginning-of-Life (BOL) Performance:

- ***Stowed Power Density: 9 kW/m^3***
- ***Areal Power Density: 300 W/m^2***
- ***Specific Power: 180 W/kg***
- ***Operational Voltage: 300 V***

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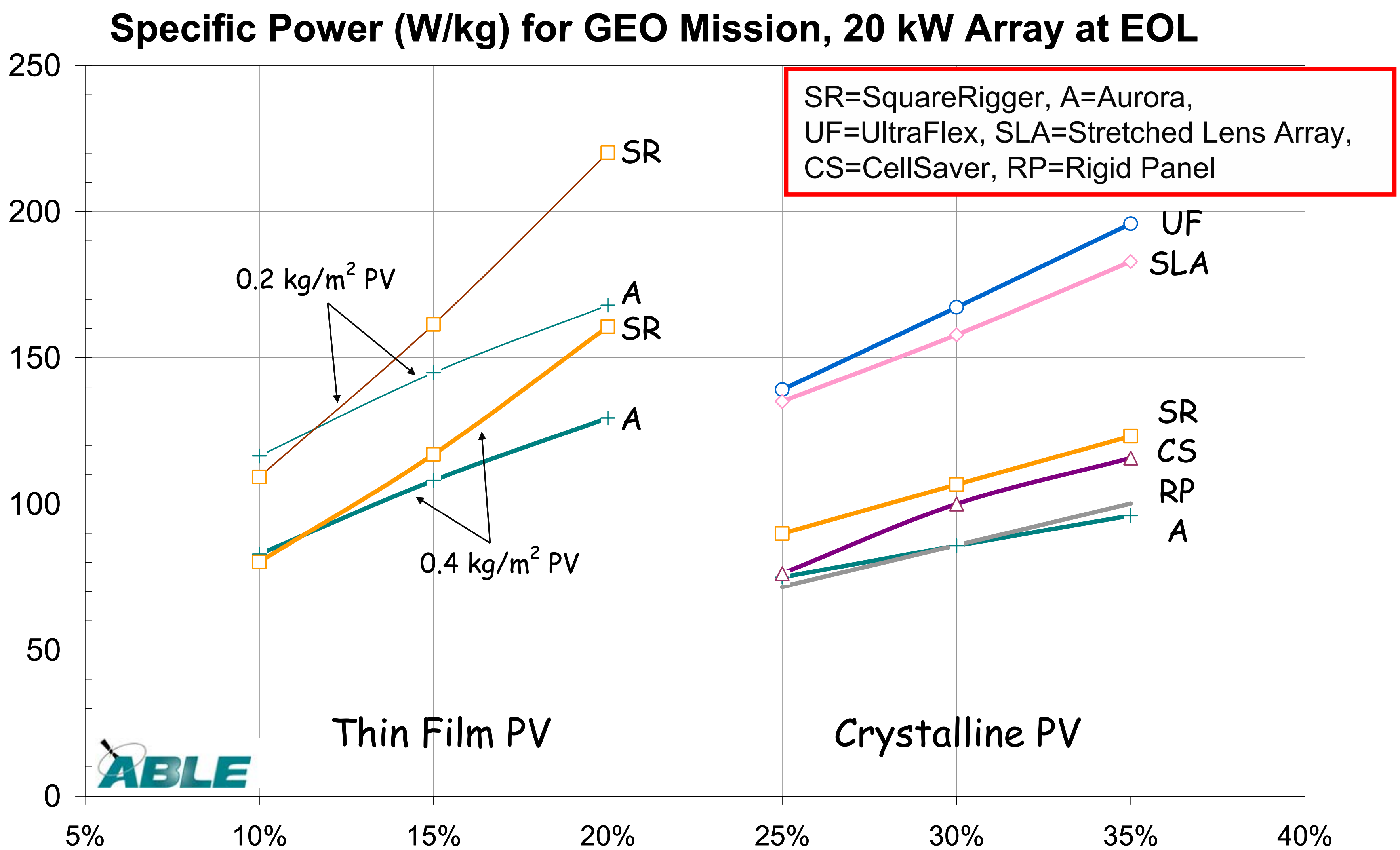
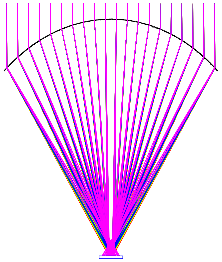
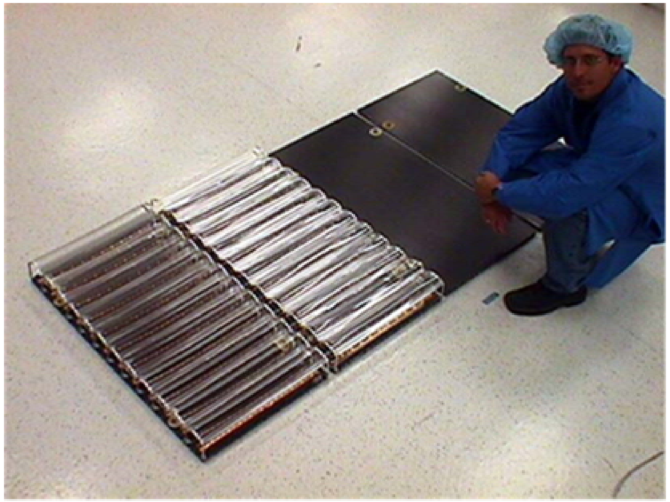
GEO Mission Array Comparisons (from Murphy et al., IEEE PVSC, 5/02)

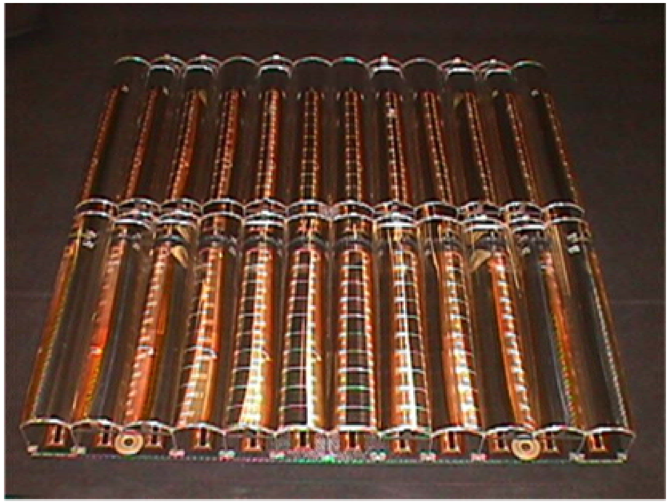




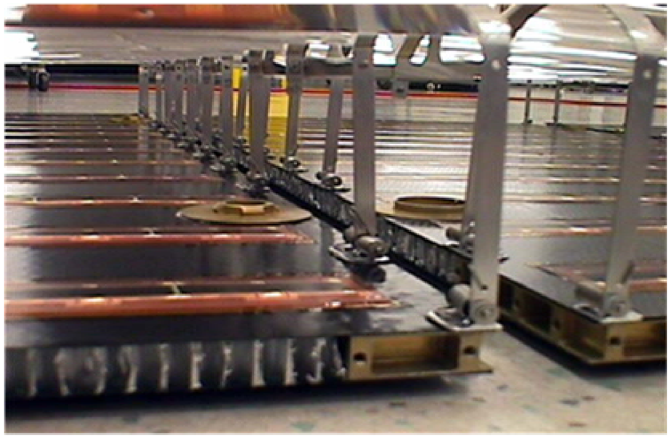
Prototype SLA Wing Hardware



Two Panels with Stretched Lenses



Two Panels with Simulated Receivers



Close-Up View Of Pop-Up Arches

Back of Picture-Frame Panel

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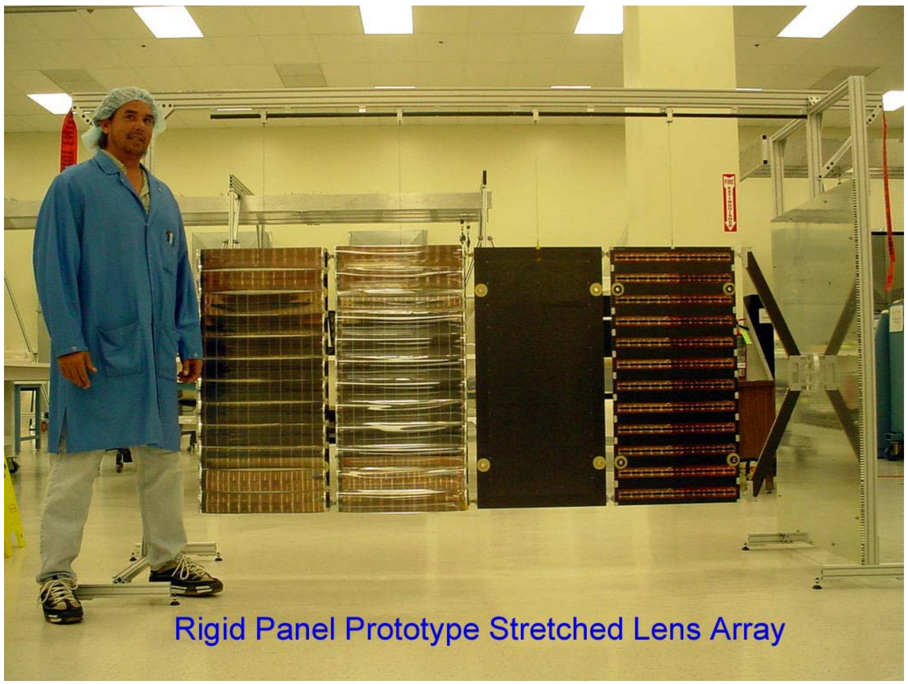
Rigid Panel SLA Prototype Array at ABLE

ABLE Engineering a PSI Company


Rigid Panel Prototype Stretched Lens Array


Prototype Rigid Panel Stretched Lens Array at ABLE

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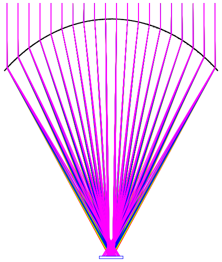
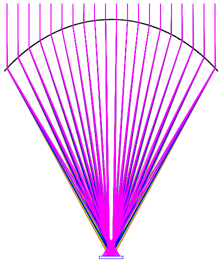
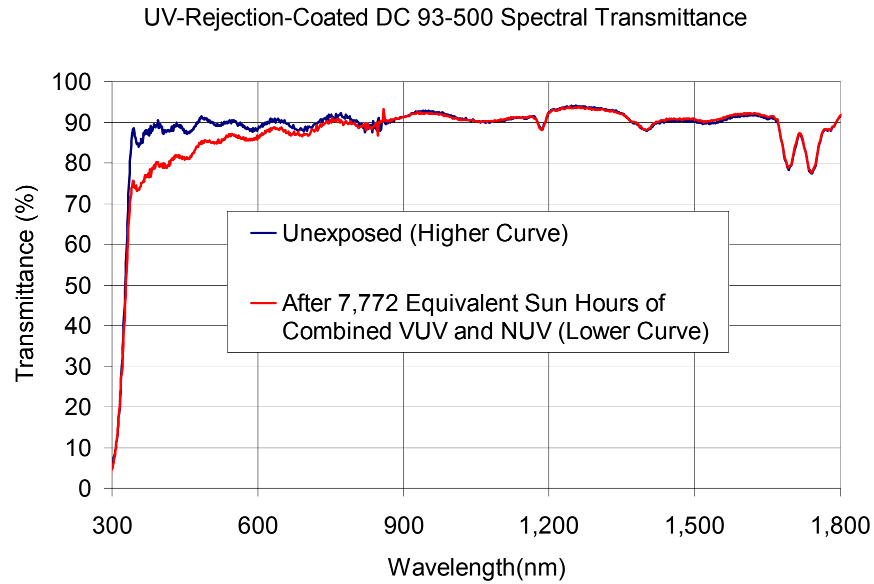


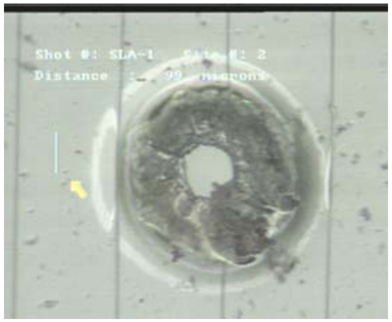
Durability Testing

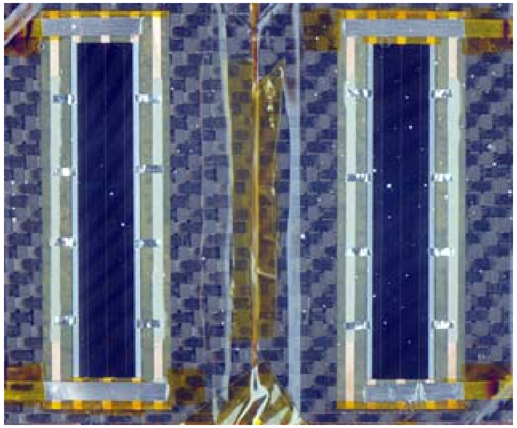


SLA Durability Testing



- ***Ultra-Thin Stretched Lens Survived 1,800 Thermal Cycles from -180C to +120C (20 Years on GEO)***
- ***Stretched Lens Maintained Optical Performance After 1x10^{15} of 1 MeV electrons per sq.cm.***
- ***Ultraviolet (VUV + NUV) Testing of Coated Lens Material Shows Only Small Degradation***
- ***Micrometeoroid Impact Tests on Stretched Lenses and Encapsulated Cells (Biased at 1,000 V Relative to Space Plasma) Showed No Lens Tearing or Electrical Arcing***





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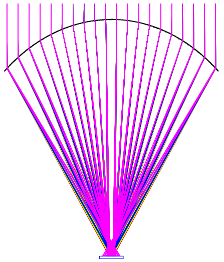
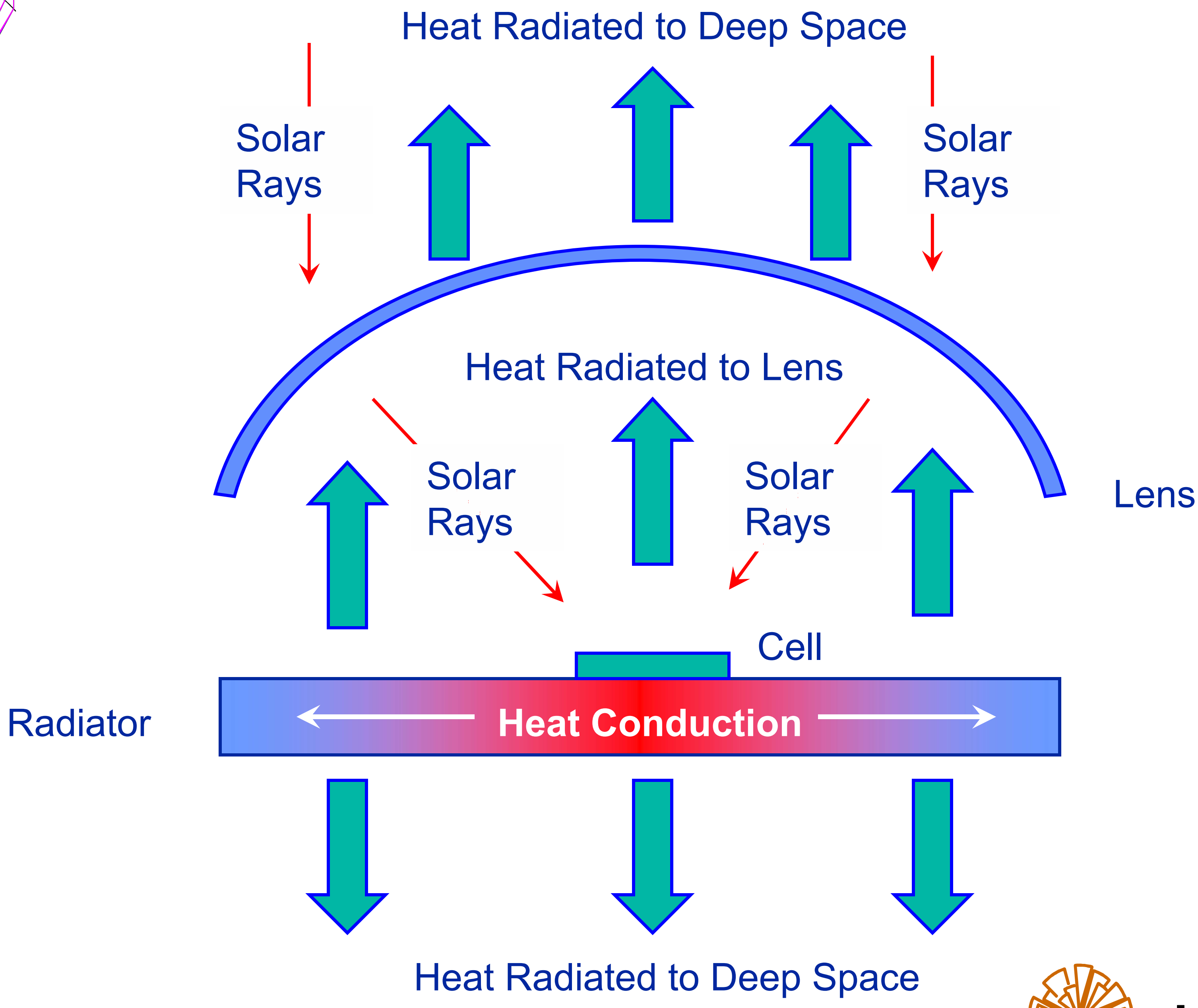
Thermal




Heat Radiated to Deep Space
Solar Rays
Solar Rays
Heat Radiated to Lens
Solar Rays
Solar Rays
Lens
Cell
Radiator
Heat Conduction
Heat Radiated to Deep Space

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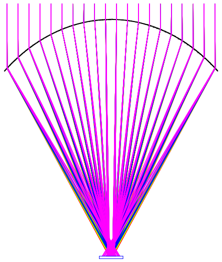
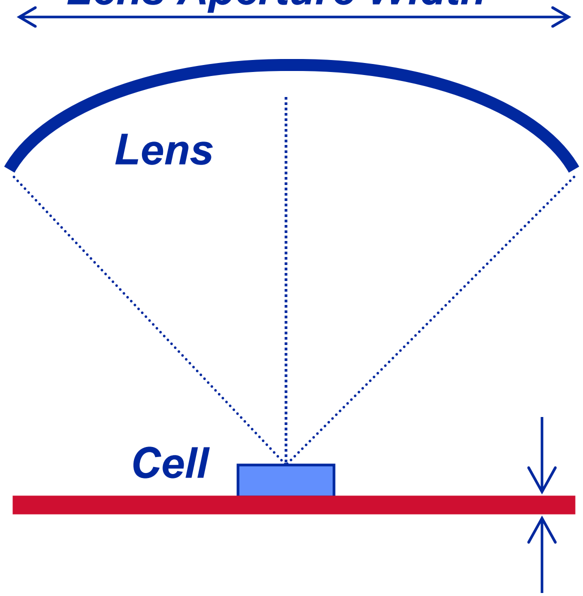
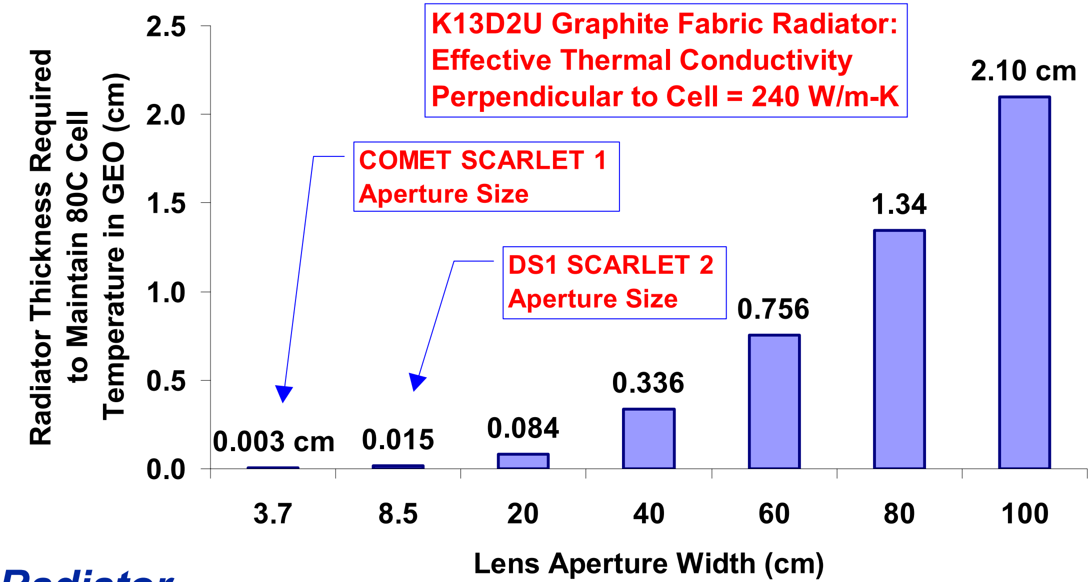


Required Radiator Thickness for Line Focus PV Concentrators with 25% Cells Depends on Scale

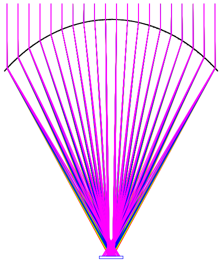




~150 Micron Thick Radiator Is Fine for Present 8.5 cm Lens Aperture Width

ENTECH, INC.

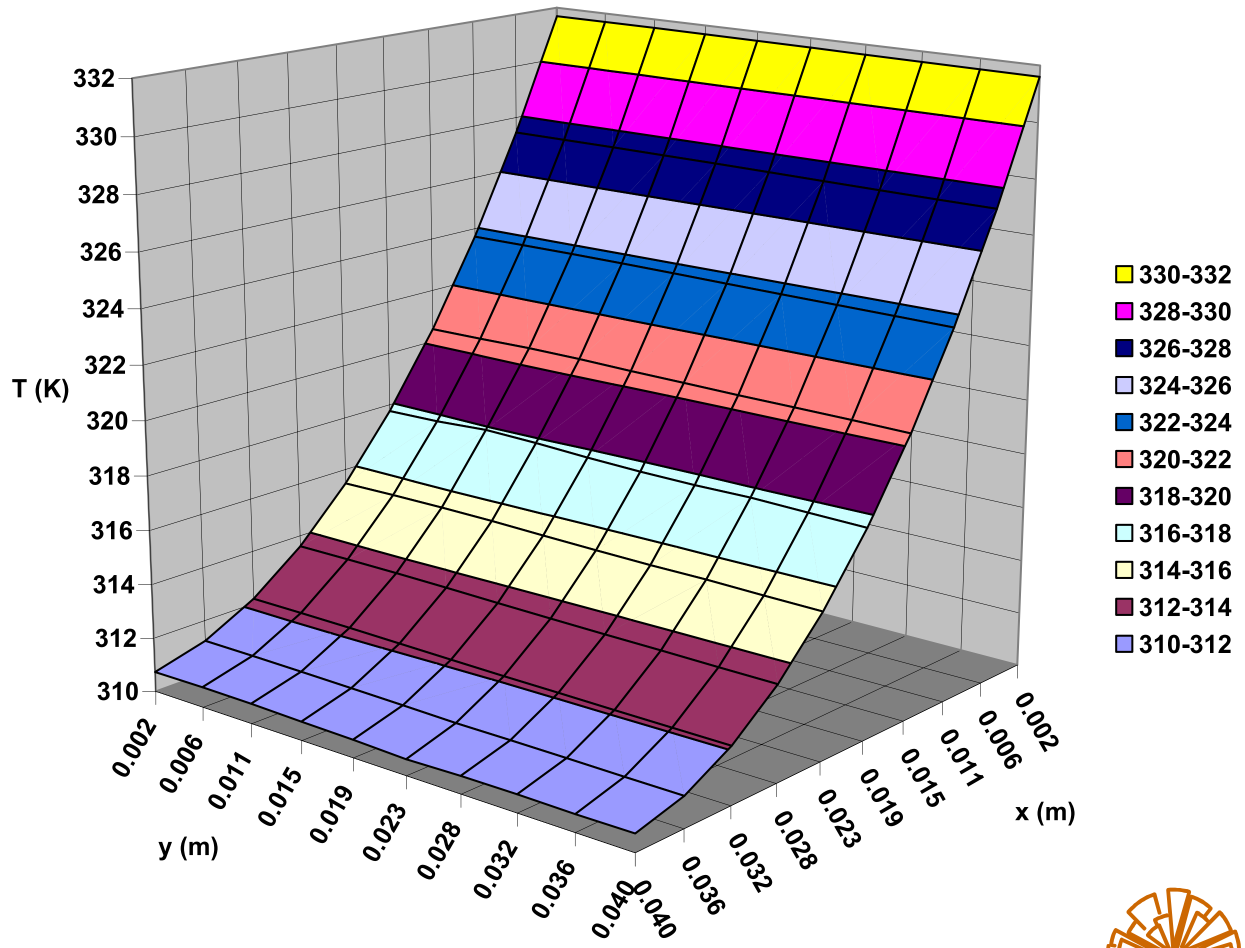
Thermal Analysis: Line Focus with 30% Cells

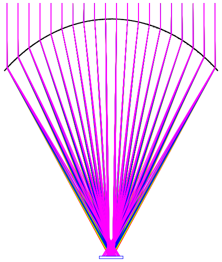


10X Linear Lens Radiator Thermal Analysis

8.5 cm Aperture Width, 30% Cell, 127 micron Radiator Thickness, GEO Orbit

Max Radiator Temperature Just Beneath Cell = 332K (59C)



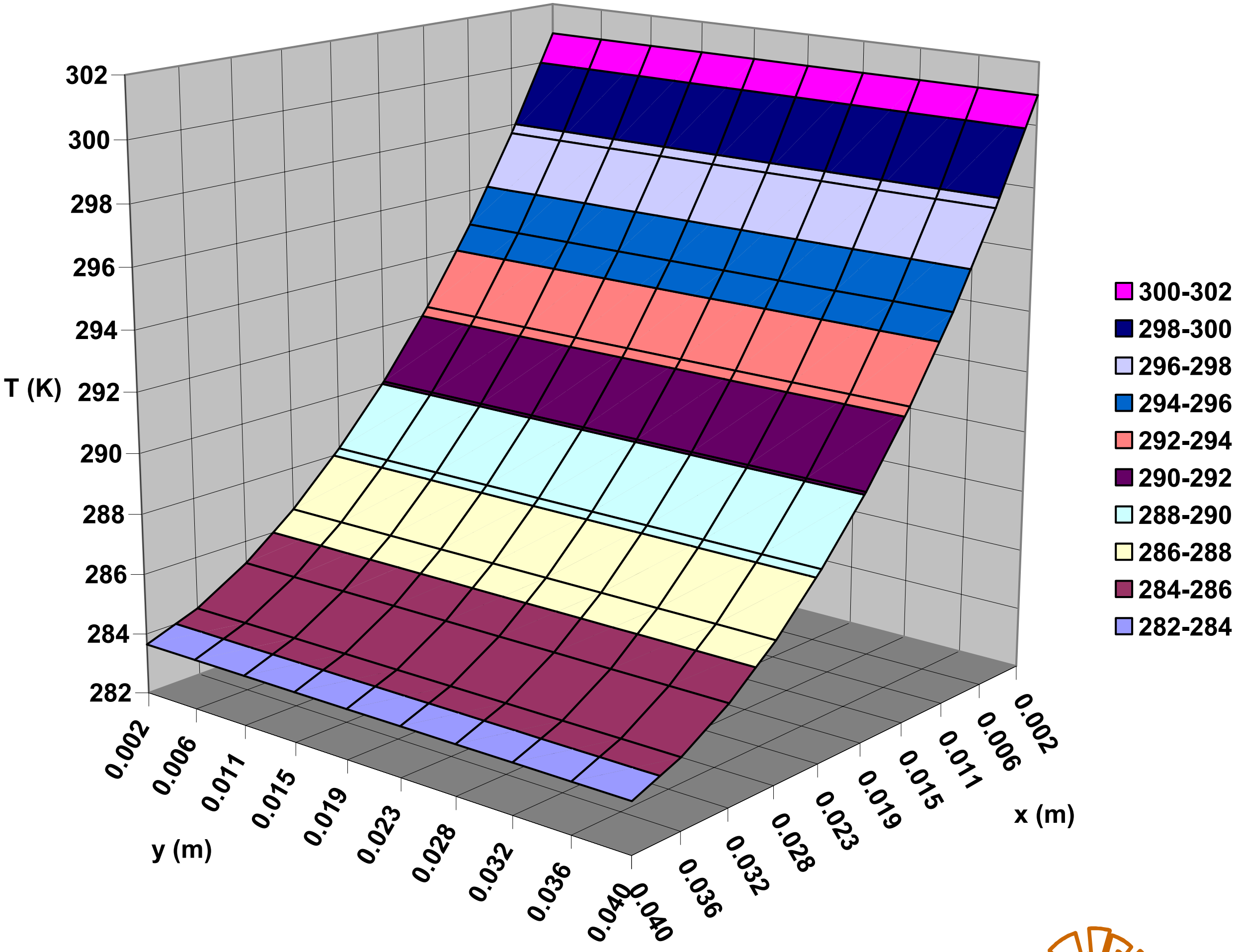


Thermal Analysis: Line Focus with 50% Cells

10X Linear Lens Radiator Thermal Analysis

8.5 cm Aperture Width, 50% Cell, 127 micron Radiator Thickness, GEO Orbit

Max Radiator Temperature Just Beneath Cell = 301K (28C)



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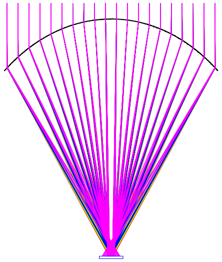

Advanced Concentrator Concepts for SSP

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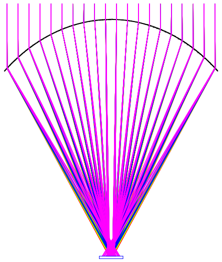
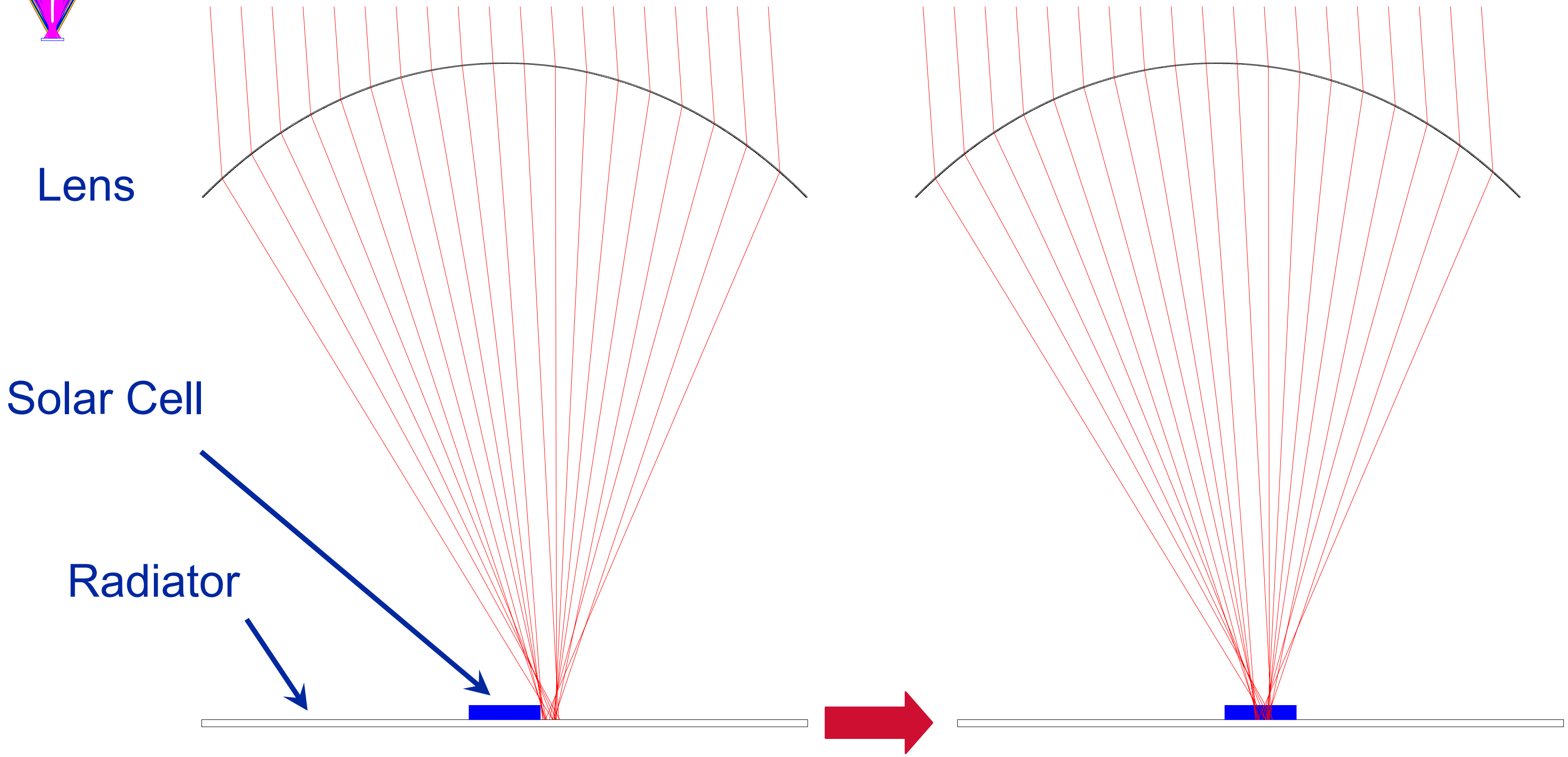


Adaptive Techniques Could Be Used to Accommodate Large SSP Deflections



Local Deflections on Square-Kilometer Scale SSP Arrays Could Cause Local Image-to-Cell Misalignment

But Adaptive Techniques Could Be Used to Translate the Local Cell/Radiator Relative to Lens to Accommodate These Deflections

A Flimsy Blanket Array with Large Deflections Can Work with a Concentrator Approach with Proper Adaptive Accommodation

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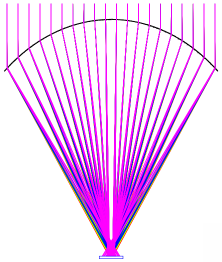
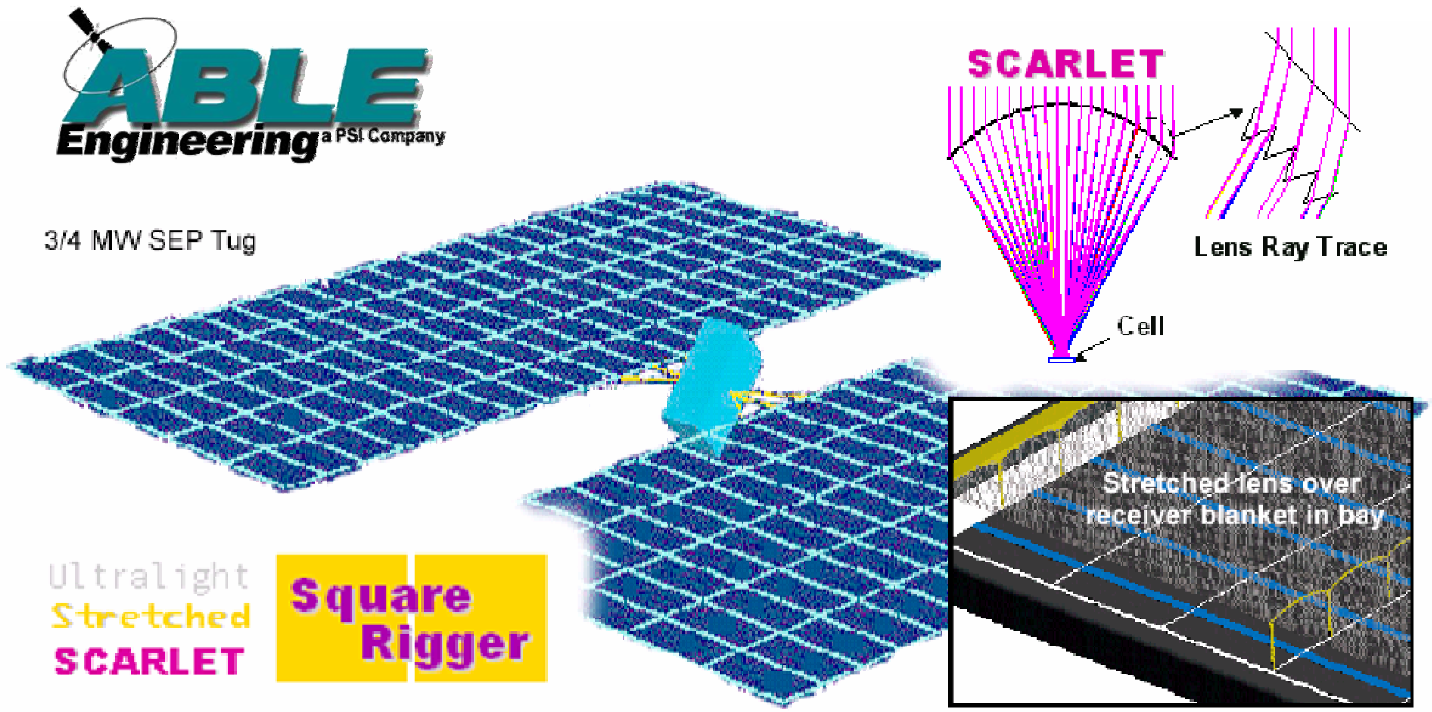


A Marriage Made in Heaven: ABLE's SquareRigger Platform and ENTECH's Stretched Lens Array



USS SquareRigger

Time Frame	< 5 Years	5-10 Years
Power Capability (kW)	100	1,000
BOL Specific Power (W/kg)	330	500
Stowed Power (kW/m^3)	80	120
Voltage	1,000	TBD

Applicable to: All NASA, DOD, and commercial spacecraft requiring high power, including:

- GEO communication satellites
- Interplanetary SEP spacecraft
- Space Solar Power
- SEP Orbital Tugs

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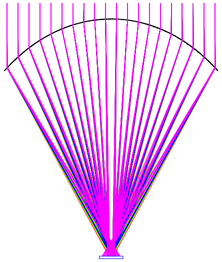
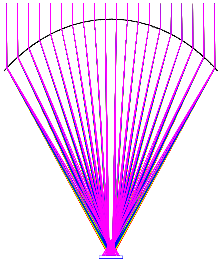
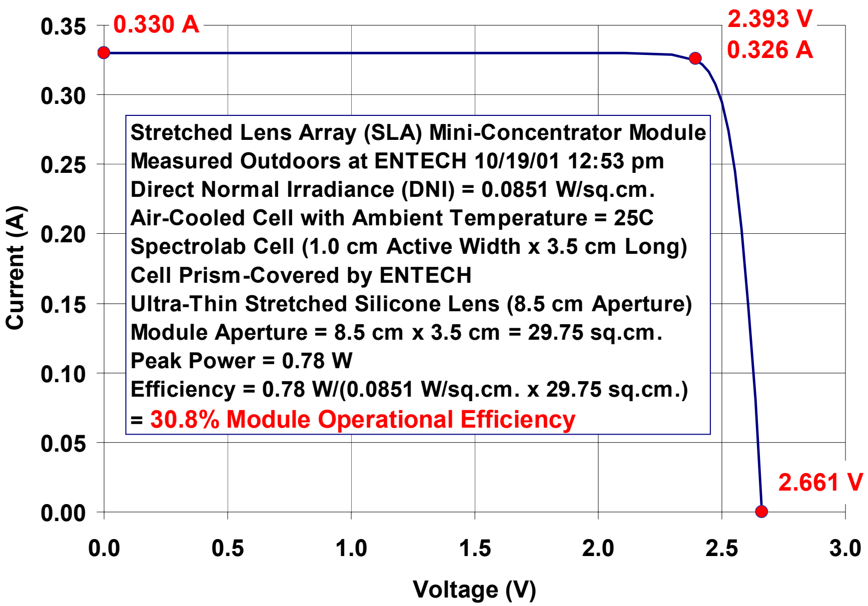


Synergy with Terrestrial Solar Power



Typical IV Curve for 30%-Efficient Mini-Concentrator Using a Spectrolab Cell



- **This Is Believed to Be the First Solar Energy Device Tested Outdoors Under Natural Sunlight at Over 30% Operational Solar-to-Electric Conversion Efficiency**
- **A Much-Larger Parabolic Dish/Stirling Engine Unit Achieved 29.4% Efficiency in 1984**
- **Despite the Obviously More Significant Power Output of the Dish/Stirling Unit (~ 25 kW), This Tiny Module (~ 1W) Shows that Photovoltaic Technology Has Now Overtaken Solar Thermal Technology in Conversion Efficiency**

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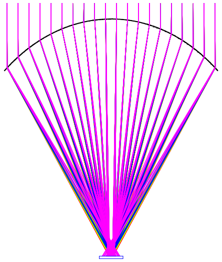

Conclusion

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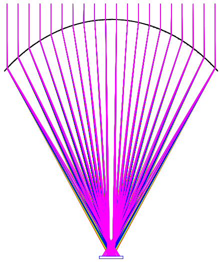

Conclusions

- Refractive Concentrators Using Multi-Junction Cells Represent the Most Efficient Option for Converting Sunlight to Electricity for Either Space or Ground Solar Power Applications
- Today's Demonstrated Lens/Cell Module Efficiencies Are 27% in Space and 30% on the Ground – Future Efficiencies at SSP Implementation (e.g., 2022) Should Nearly Double Based on Cell Efficiency Trends
- Compared to Thin Film Arrays, Refractive Concentrator Arrays Will Be 2-4X More Efficient, 2-4X Smaller in Size, and Equal or Better in Terms of W/kg and $/W at the System Level
- Work Should Continue on Advanced Concentrator Arrays for SSP, Including Advanced Ultra-Light Concepts and Simple Means to Accommodate Large Deflections on Square-Kilometer Size Arrays, Using Techniques from Adaptive Optics, Smart Materials, Shape Memory Alloys, etc.

ENTECH, INC.